



Plug-In Hybrid Electric Vehicles and the Vermont Grid: A Scoping Analysis

Literature Review and Proposed Methodology



CVPS converted Toyota Prius now on loan to a Green Mountain College research project. Photo courtesy of CVPS.

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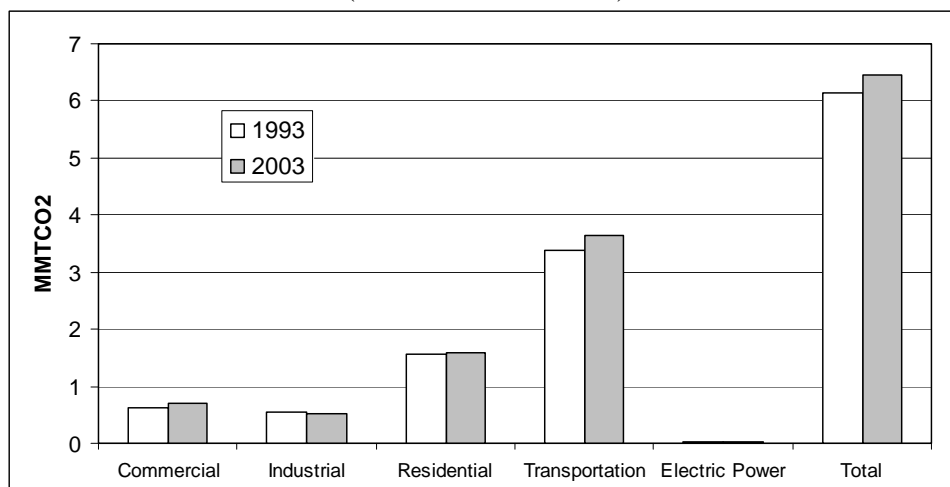
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I. Introduction

The transportation sector is the leading contributor of carbon dioxide emissions in Vermont. Furthermore, as illustrated in Figure 1, carbon dioxide emissions in the transportation sector increased to a greater degree during the ten years from 1993 and 2003 than in any other sector. Vermont must address its transport-related emissions of carbon dioxide if it is going to do its part to address global climate change, arguably the most critical environmental issue facing humanity.

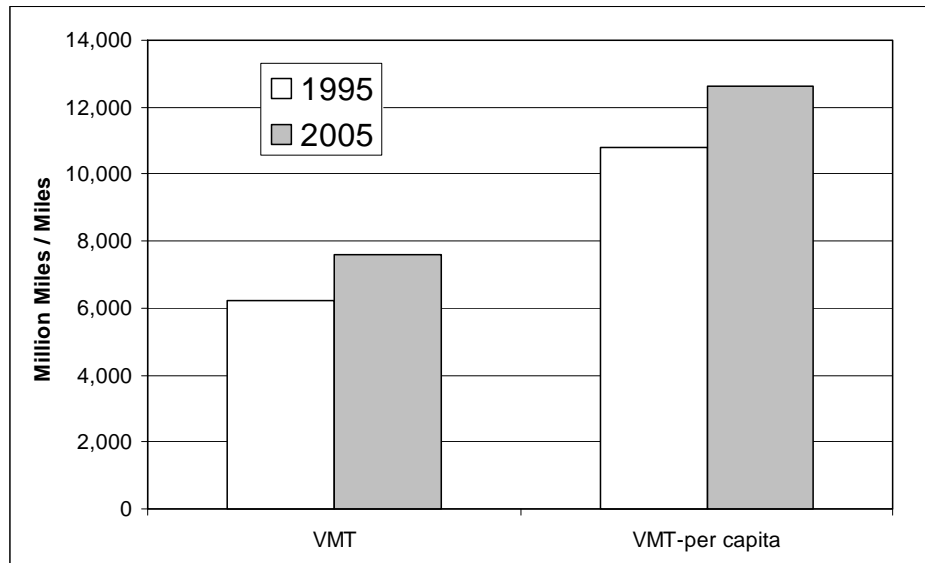
Figure 1
Vermont CO₂ Emissions by Sector: 1993 vs. 2003
(Million Metric Tons)



Source: US DOE Energy Information Administration

Although total vehicle miles traveled (VMT) in Vermont have declined slightly in recent years, likely due to higher fuel prices, longer term trends indicate that Vermonters are driving more today than they did a decade ago. Figure 2 compares total VMT and per capita VMT from 1995 and 2005. Per capita vehicle miles traveled in Vermont increased by 17 percent between 1995 and 2005. Per capita VMT in Vermont in 2005 were 12,600, well above the national per capita VMT of just over 10,000. Total VMT in Vermont currently stands at just over the 7.5 billion mark (Watts, Glitman and Wang, 2007).

Figure 2
Total VMT and Per Capita VMT in Vermont: 1995 vs. 2005



Source: Vermont Agency of Transportation

Gasoline prices in New England have risen significantly over the past decade at the same time that the demand for automobile travel has increased. As a result, Vermonters are forced to allocate more of their income to transportation. In 2006, Vermonters consumed 344 million gallons of gasoline and 72 million gallons of diesel fuel at a total expenditure of \$1.1 billion dollars. Expenditures on transportation fuels in 2006 were up over \$500 million from 2002 due to rising fuel prices (Watts, Glitman and Wang, 2007). Most of the money spent on fueling vehicles each year in Vermont leaves the state to outside interests—the so called “leaky bucket” phenomena.

Advances in electric drive systems and energy storage devices have made hybrid electric vehicles a reality. In 2006, 1.5 percent of all new vehicles sold were hybrids (www.hybridcars.com). Data from the Vermont Department of Motor Vehicles indicates that a total of 2,389 hybrid electric vehicles are registered in the state. A growing national movement is calling for the automobile manufacturers to develop the next generation hybrid electric vehicles that allow charging from the electric grid. These plug in hybrid electric vehicles (PHEVs) offer the potential for the light vehicle fleet to substitute electricity supplied from the grid for gasoline purchased at the pump. Prototype PHEVs have demonstrated the ability to achieve over 100 miles of travel per gallon of gasoline consumed (www.calcars.org). Furthermore, studies have found that the cost of electricity to drive the same distance as a gallon of gasoline is less than one dollar.

A PHEV differs from a conventional hybrid electric vehicle commercially available today in two important ways. First, additional battery storage and a three-pronged plug allow a PHEV to displace gasoline with electricity purchased from their local utility. Conventional hybrids use the battery pack in what is described as a charge sustaining mode, meaning the battery pack is subject to shallow cycles of discharging and charging from the vehicle engine and the regenerative braking system. In contrast, a PHEV uses a charge depletion strategy, whereby it uses a much greater percentage of the battery pack for vehicle operations (Gonder and Markel, 2007). Once the battery pack is nearing depletion, the vehicle reverts back to a charge sustaining mode similar to its non plug-in counterpart.

PHEVS are often categorized by the potential all-electric range given different battery pack storage capacities. A PHEV20 offers sufficient energy storage to deliver 20 miles of travel in all-electric mode. Similarly a PHEV40 has a larger battery pack than a PHEV20, and thus has the potential to travel 40 miles in all-electric mode. While all-electric range is a useful way to characterize PHEVs, these vehicles will likely operate in a blended mode using both the engine and an electric motor to propel the vehicle in an effort to optimize the overall efficiency and cost of the vehicle (Gonder and Markel, 2007).

PHEVs could offer Vermont the ability to keep a portion of its transportation dollars in state and at the same time reduce household transportation-related expenses and emissions of greenhouse gases and other pollutants. As Figure 1 above illustrates, Vermont has a low-carbon electricity supply mix, thus shifting some portion of energy used for transportation from gasoline to electricity should result in a reduction in greenhouse gas emissions. Furthermore, using the idle capacity of Vermont's electric power infrastructure can serve to increase its utilization, thus putting downward pressure on electricity rates. To date, however, there is no conclusive assessment of the PHEV opportunity in Vermont. The University of Vermont's Transportation Center, in conjunction with the state's leading electric utility companies, has launched the first ever study to understand the grid impacts of an emerging fleet of PHEVs in Vermont. Specifically, the study's main objectives are:

- 1) How many PHEVs could the Vermont electric power system charge without the need to build additional generation, transmission, and/or distribution facilities assuming three plausible consumer charging patterns?
- 2) How much gasoline could be displaced annually from three different PHEV penetration scenarios—low, medium, and high—in Vermont?
- 3) What are the net regional emissions impacts from the introduction of PHEVs in Vermont, including greenhouse gas emissions and other key pollutants?
- 4) From an end-user perspective how do consumers evaluate the economics of PHEVs? This will include calculations of the MPG equivalent cost of displacing gasoline with electricity.

While no PHEVs are currently being sold today, there are a number prototypes currently being tested. The Electric Power Research Institute and DaimlerChrysler have several PHEV Sprinter vans being evaluated in different locations in the US and Europe. Three start-up companies have developed retrofit kits that convert existing hybrid electric vehicles to PHEVs. One of these companies based in Toronto, Canada called Hymotion, recently converted two Toyota Prius vehicles for Vermont's largest utility, Central Vermont Public Service. Researchers at Green Mountain College in Poultney, Vermont are gathering performance data on these vehicles under the direction of Steven Letendre.

It now appears that the major automobile manufacturers are planning to offer PHEV products within the next several years. General Motors Corporation has announced plans to offer two PHEV options, one being a version of its Saturn Vue SUV and the other a new model referred to as the Volt. Very recently, Toyota announced that it would be testing several PHEVs based on the Prius platform in Japan and the US. It appears imminent that Toyota will soon manufacture and sell a commercial PHEV product. Ford Motor Company and the electric utility company Southern California Edison also recently announced plans to test PHEV versions of the Ford Escape. In addition, there are several pure electric vehicle developers that have plans to offer products in the next 12 months. These include Tesla Motors with its two-seater all electric sports car and Phoenix Motors Cars, which is producing and marketing an all electric four-door truck for fleet applications.

Given these developments, it is important to understand the potential of the Vermont grid to accommodate a growing number of grid-connected cars over the coming decades. Furthermore, it is important to understand this potential particularly as Vermont is faced with important decisions about its power supply as contracts with Hydro Quebec and Vermont Yankee are set to expire. In addition, it is useful to understand the implications from a potential shift from tailpipe emissions to power plant emissions associated with a transition to PHEVs and other electric drive vehicles. And finally, energy security is a vital issue for the nation and Vermont. Understanding the petroleum displacement benefits of a transition to electric drive, along with the economic benefits, is helpful to policymakers as they devise policies to address climate change and strengthen local economies.

II. Literature Review

The oldest PHEV development program is housed at the University of California Davis, where Professor Andrew Frank has worked with students for two decades designing and building prototype PHEVs (www.team-fate.net). Since 1999, much of the technical work on defining and characterizing PHEV technology has occurred under the auspices of the Hybrid Electric Vehicle Working Group (WG) convened by the Electric Power Research Institute (EPRI), an electric industry-supported research organization. EPRI brought together representatives from the electric utility and automotive industries, the US Department of Energy and its laboratories, other regulatory agencies, and university research centers to study a wide range of technical issues related to PHEV development. A WG report published by EPRI (2001) titled *Comparing the benefits and impacts of hybrid electric vehicle options* concluded:

This report indicates that HEVs, including grid-connected (plug-in) models, can probably be designed for a wide variety of vehicle platforms meeting performance characteristics customers are familiar with. Plug-in hybrids provide significantly improved fuel economy over conventional vehicles, reductions in greenhouse and smog precursor emissions, and petroleum use. However, HEVs, especially plug-in HEVs with an all-electric capability, cost more than conventional vehicles. HEVs are expensive due to complex motors and chargers and the energy storage required. Battery life and costs are challenges that need to be addressed. Potential battery replacements can significantly increase the vehicle's life-cycle cost.

The Customer Survey indicated that people preferred plugging in a vehicle instead of going to the gas station. The study also indicated a large market potential for all HEVs—if cost equivalence with conventional vehicles can be achieved and significant even when priced 25% more than a conventional vehicle counterpart. (EPRI, 2001, p. vi)

A. PHEV Technical Specifications

The PHEV technical specifications that emerged from two of the WG reports have served as a basis for most research on PHEV grid impacts. EPRI (2001) study cited above provides specifications for a mid-sized sedan PHEV and EPRI (2002) titled *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles* provides technical specifications for a compact sedan, and mid-sized and full-sized SUVs. Table 1 lists the technical specifications on PHEV technology described in the reports.

Table 1
 Technical Specifications for PHEV20 in Compact Sedan, Mid-Size Sedan, Mid-Size SUV, and Full-Size SUV Vehicle Platforms

	PHEV20 compact sedan	PHEV20 mid-size sedan	PHEV20 mid-size SUV	PHEV20 full-size SUV
Motor Rated Power, kW	37	51	84	98
Nominal Battery Pack Size, kWh	5.1	5.9	7.9	9.3
Battery Rated Capacity, usable kWh [†]	4.1	4.7	6.3	7.4
Gasoline mpg (PHEV/conventional vehicle)	52.7/37.7	43.5/28.9	34.7/22.2	29.5/18.2
Electric Only Economy (mpege)*	134	117	90.5	77
All Electric Efficiency (miles/kWh)	4.0	3.49	2.7	2.3
Mileage Weighted Probability Fuel Economy (mpege) [@]	71.7	58	46.6	39.8
Vehicle Mass, kg	1,292	1,664	2,402	2,824
Charging time (hours, 120 V 15 amp, 1 kWh/hr.) [^]	4	4.7	6.3	7.4
Charging time (hours, 120 V 20 amp, 1.3kWh/hr.) [^]	3	3.5	4.7	5.6
Charging time (hours, 240 V 40 amp, 5.7 kWh/hr.) [^]	0.7	0.8	1.1	1.3

[†]The battery rated size is assumed to be 80% of the nominal pack size.

*The report expresses the all electric range as miles per energy equivalent gasoline gallon (mpege). This calculation assumes 33.44 kWh per gallon of gasoline.

[@]The mileage weighted probability (MWP) fuel economy provides an estimate of a blended electric/gasoline operation efficiency. The MWP gives an estimation of what portion of PHEV's daily annual mileage will be in all electric mode based on national driving statistics. The values presented in the table assume nightly charging of the vehicle.

[^]The charging rate per hour assumes an 80% required safety factor for continuous charging and assumes an 82% efficiency for 120 V chargers and 87% for 240 V chargers and 85% battery efficiency.

The vehicle parameters evolved through sophisticated vehicle design modeling using a tool known as ADVISOR (ADvanced VehIcle SimulatOR), which was developed by researchers at the National Renewable Energy Laboratory, one of the US Department of Energy’s research laboratories. It is important to note that the vehicle fuel economy, a critical parameter for understanding PHEVs, is dependent on a number of key factors including the drive cycle and the frequency of charging. Table 1 above reports three different fuel economy measures.

The first measure of fuel economy in Table 1 is the gasoline miles per gallon, which indicates the lower bound mileage number based on the vehicle operating in charging sustaining mode similar to conventional hybrid vehicles sold today. The second fuel economy measure is based on operation of the vehicle in electric-only mode and is expressed as miles per energy equivalent gasoline gallon (mpege). The energy content of a gallon of gasoline is expressed in terms of electrical energy at 33.44 kWh per gallon to derive this value. The mpege serves as the upper bound efficiency potential of the vehicle. The “Mileage Weighted Probability Fuel Economy” presented in Table 1 is an attempt to present a likely “real world” fuel economy estimate based on a statistical approximation of the number of miles driven each year in all-electric mode and with the vehicle being recharged nightly.

The two EPRI WG studies also present vehicle parameters for PHEV60s—plug-in hybrid vehicles with a 60 mile all-electric range. These vehicles achieve better fuel economies for each of the three measures presented in Table 1, although this is not a simple multiple due to the higher vehicle mass resulting from a larger battery pack.

Finally, it should be noted that the technical parameters of PHEVs developed by the EPRI WG may not necessarily conform to those of PHEVs that ultimately reach the market. While it is very likely that major vehicle manufacturers are doing their own vehicle design work, this information is not readily available to the public. As a result, the WG PHEV technical specifications serve as the best approximation in terms of what to expect regarding PHEV characteristics and performance. As a result, these values have served as key inputs to research on PHEV grid impacts.

B. PHEV Grid Impact Studies

Four prominent studies analyzed the grid impacts from an emerging fleet of PHEVs. While there are some similarities across the studies, each one takes a different approach in terms of the electric system, PHEV configurations, and charging scenarios analyzed. In the end, however, each study finds that the existing electric power infrastructure is capable of charging a large fleet of PHEVs without the need to build additional generating, transmission, or distribution infrastructure. Table 2 lists the studies reviewed here, along with some key features of each.

Table 2
PHEV Grid Impact Studies

Title	Authors' Affiliation	Geographic Focus	Vehicle Configuration	Charging Scenario(s)	Emissions Assessment
Impacts Assessment of Plug-In Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids	Pacific Northwest National Laboratory	Entire U.S., based on 12 modified North American Electric Reliability Council regions	PHEV33, this vehicle configuration is used to estimate the electricity consumption that would satisfy the average daily commute as determined by travel survey data.	The study assumes all excess capacity is used. Produces estimates based on 24-hour charging and 12-hour charging scenarios.	Yes
An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles	National Renewable Energy Laboratory	Six different geographic regions, using hourly load data from electric utility control areas.	This study simulated the energy requirements of a PHEV fleet that meets on average 40% of its daily miles traveled with electricity. This translates into a PHEV with an all-electric range between 20 and 40 miles	Charging is based on an optimized 24-hour cycle assuming direct utility control of when the vehicles are charged.	No
Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory	National Renewable Laboratory	This study was focused specifically on Xcel Energy's Colorado service territory.	A mid-size PHEV20 vehicle with 37 mpg gasoline and 2.78 miles/kWh and 7.2 kWh of battery storage capacity.	Four charging scenarios were evaluated: uncontrolled charging; delayed charging; off-peak charging; and continuous charging.	Yes
Effects of Plug-In Hybrid Electric Vehicles in California Energy Markets	Energy and Resources Group at the University of California Berkeley	This study used load data from the California Independent System Operator and thus was focused exclusively on CA.	A compact PHEV20 vehicle with 50 mpg gasoline, 130 mpeg, and 5 kWh of usable stored energy. Also conducted sensitivity analysis using a full-size SUV.	Three charging scenarios were modeled: optimal charging, evening charging, and twice a day charging.	No

The study conducted by researchers at the Pacific Northwest National Laboratory (PNL) adopted what might be described as a top down approach. In each of the 12 North American Electric Reliability Council regions 24-hour load profiles were developed for a typical summer day and a typical winter day. This simplification from an 8,760 load profile is justified by the fact that these two periods are likely to have the least reserve capacity relative to the other times of the year (Kintner-Meyer, Schneider, and Pratt, 2007). The two load profiles were used to estimate the unused generating capacity in each region. The study calculates the number of PHEVs that could be charged with this excess generating capacity. It should be noted that the study did not include peaking plants as available for PHEV charging, given that these units are designed for short run-times and thus would likely be uneconomic to have running for extended periods.

Nationwide, the PNL study estimates that 73 percent of energy for the light-duty vehicle (LDV) fleet could be supported by the existing US electric power infrastructure, assuming a daily drive of 33 miles on average. This is considered the “technical” potential given the current installed generating capacity installed nationwide, which represents 217 million vehicles. In this scenario, the power sector would be running at near full capacity most hours of the day. The authors recognize that this would put strain on the system, which was engineered to meet widely fluctuating demands for power. As a result, the authors assess a second scenario whereby PHEVs can only charge for 12 hours each day, between the hours of 6:00 pm and 6:00 am. In this case, 43 percent of the energy of the nation’s LDV fleet could be supplied by the existing electric power infrastructure.

The study identified significant difference between regions regarding the electric power systems’ ability to charge an emerging fleet of PHEVs. For example, the technical potential of the region

referred to as CNV (California and Southern Nevada) is only 23 percent of the energy requirements of the LDV fleet in that region. In the US section of the Northeast Power Coordination Council (New York and the six New England States) region, the study estimates that 80 percent of the energy requirements of the light vehicle fleet could be met by the regional electric grid, or approximately 20 million vehicles.

The remaining PHEV grid-impact studies can be referred to as bottom up or scenario analyses. Different PHEV penetration scenarios are assessed to better understand the demands that charging PHEVs would place on regional grids. The Denholm and Short (2006) study used a PHEV load tool to incrementally add load to six different electric power systems assuming an optimal, utility-controlled charging regime to estimate the number of PHEVs that could be charged without adding to the region's system peak load. They found that vehicle penetration rates as high as 50 percent of the regional light vehicle fleets could be met given the existing generation capacity in each of the six study areas, assuming that 40 percent of the daily vehicle miles come from electricity. This level of PHEV penetration would increase the annual energy demand by 6 to 12 percent depending on the region. They also identified additional ancillary benefits in the form of increased loading of base load power plants and reduced cycling of intermediate generating resources; both of these factors could potentially lower overall operating costs.

The remaining two studies were much more geographically focused. Parks, Denholm, and Markel (2007) used a sophisticated production cost model known as PROSYM to model Xcel Energy Colorado's power system to investigate the implications of an emerging fleet of PHEVs in their service territory. Xcel Energy provides electricity to 3.3 million customers in eight states. In Colorado, Xcel serves 1.3 million customers and delivers 26,500 GWh of energy annually.

The Xcel study, as referenced in Table 2, used a PHEV20 vehicle configuration to model the utility system impacts of 500,000 vehicles, roughly 30 percent of the 1.7 million vehicles in the Xcel service territory. Three charging scenarios were analyzed to understand the power system impacts of a range of possible consumer charging preferences. Parks, Denholm, and Markel (2007) define the study's charging scenarios as follows:

- **Case 1: Uncontrolled Charging:** The uncontrolled charging case considers a simple PHEV scenario where vehicle owners charge their vehicles exclusively at home in an uncontrolled manner.
- **Case 2: Delayed Charging:** The delayed charging case is similar to Case 1, in that all charging occurs at home. However, it attempts to better optimize the utilization of low-cost off-peak energy by delaying initiation of household charging until 10 p.m.
- **Case 3: Off-Peak Charging:** The off-peak charging scenario also assumes that all charging occurs at home in the overnight hours. However, it attempts to provide the most optimal, low-cost charging electricity by assuming that vehicle charging can be controlled directly or indirectly by the local utility.
- **Case 4: Continuous Charging:** The continuous charging scenario is similar to Case 1, in that it assumes that charging occurs in an uncontrolled fashion (at 1.4 kW) whenever the vehicle is plugged in. However, it also assumes that public charging stations are available wherever the vehicle is parked.

(Parks, Denholm, and Merkal, 2007, pp. 7 – 10)

Not surprisingly, the uncontrolled and continuous charging added considerable load that is coincident with periods of high power demands in both the summer and winter months. However, the impacts were quite modest, with the uncontrolled charging scenario adding 2.5 percent to the system peak demand and the continuous charging scenario adding 4.6 percent. In terms of energy, charging 500,000 PHEVs from Xcel Colorado would add 3 percent to the total energy required annually, again assuming a PHEV20 that derives 39 percent of its drive energy from electricity. Furthermore, the authors of this study conclude that if modest steps were taken to encourage optimal charging a massive penetration of PHEVs could be accommodated without adding to Xcel Colorado's system peak. The greatest system-wide benefits could be achieved through direct utility control of PHEV charging.

The Lemoine, Kammen, and Farrell (2007) study from the University of California Berkeley focused its PHEV assessment on the State of California. In addition to assessing system load impacts, this study evaluated the economic trade-offs between charging from the grid versus using gasoline to fuel a vehicle. Like the previous study discussed above, the authors select a PHEV20 as a base case to assess the economics of PHEV charging and system load impacts. Sensitivity analysis was conducted assuming a full-size SUV configuration with a gasoline economy rating of 30 mpg and 8.7 kWh of usable electricity to meet the 20 mile all-electric range target.

Using 1999 wholesale power prices, the authors estimate the number of vehicles that could charge economically from the California grid (e.g., electricity would serve as a less expensive fuel as compared to gasoline). Residual PHEV electricity supply curves were constructed along with PHEV electricity demand curves based on various gasoline prices. The analysis found that 6 million vehicles could charge economically off-peak and 3 million on-peak if gasoline prices are assumed to be \$3 per gallon. This "economic" potential represents a significant portion of the 17 million vehicles located in the study region.

The grid impact assessment was based on three different PHEV penetration scenarios and three different vehicle charging assumptions. The system load impacts were calculated for 1, 5, and 10 million PHEVs charging from the California grid, assuming an effective charging rate of 1 kWh per hour. The three charging scenarios analyzed were defined as follows:

1) Optimal Charging. This corresponds to the best case assumptions used in prior analyses. It is optimal from the grid operator's perspective. The vehicles are charged in a pattern that smoothes demand as much as possible by charging during periods of lowest demand, and vehicles need not charge for 5 continuous hours. This scenario bounds the possible beneficial load-leveling effects of PHEVs.

2) Evening Charging. The times at which the PHEVs begin charging are evenly distributed between 6, 7, and 8 PM. Each PHEV charges for 5 continuous hours. This represents drivers returning home from work and plugging in their vehicles. This and the next scenario are meant to provide worst-case baselines for possible behavior in the absence of price incentives or technical means of shaping charging patterns.

3) Twice Per Day Charging. This is a high demand scenario: each PHEV is assumed to be plugged in to charge fully at the end of each commute leg. Thus, each vehicle fully charges twice each day, once upon arriving at work in the morning and once upon arriving home in the evening. Charging start times are evenly distributed between 8 and 9 AM and again between 6, 7, and 8 PM. Each PHEV charges for 5 continuous hours in the morning and again in the evening.

(Lemoine, Kammen, and Farrell, 2007, p. 4)

Under all three charging regimes the system level impacts of 1 million PHEVs do not cause any major problems. However, the 5 and 10 million PHEV scenarios would clearly increase peak demand under the evening charging and twice per day charging scenarios. The authors note that even 1 million vehicles charging during peak price hours could increase the price of electricity for everyone, and thus public pressure to strongly encourage off peak charging could emerge. The study concludes that it is unlikely that a large fleet of PHEVs will emerge in the next decade given that the fuel savings over the life of the vehicle is likely not sufficient to justify the initial price premium of a PHEV over a conventional internal combustion engine or currently available non-plug in hybrid vehicles (Lemoine, Kammen, and Farrell, 2007).

All four of the PHEV grid impact studies reviewed here demonstrate that the electric power infrastructure currently in place throughout the nation's regional grids could charge a large fleet of PHEVs. Even large penetrations of PHEVs represent a small increase in the total electrical energy consumed nationwide. Direct utility control of charging is the optimal approach to avoid having PHEV charging contribute to system peak demand, and thus offers the best chance to efficiently and economically integrate PHEVs into the nation's vehicle fleet. Price incentives to consumers could increase the likelihood of off-peak charging.

C. PHEV Net Emissions Implications

PHEVs allow greater use of electricity as transportation fuel, thereby displacing gasoline. From an emissions perspective, this entails substituting tailpipe emissions from vehicles for emissions discharged from the stacks of large, central-station power plants. For human health, ecosystem protection, and existing air quality regulations, it is important to understand the net emissions impacts associated with greater use of electricity for fueling the nation's light vehicle fleet.

The EPRI WG studies calculated the net greenhouse gas emissions and smog precursor emissions on a per vehicle basis to allow for comparisons. Two of the grid impact studies also assessed the net emission impacts from an emerging fleet of PHEVs. Researchers at the National Renewable Energy Laboratory produced an analysis of the potential carbon emissions reduction by 2030 from PHEVs. This study was part of a larger project initiated by the American Solar Energy Society (ASES) to assess potential carbon emissions reductions in all sectors by 2030. In early 2007, ASES published a comprehensive report based on the project's findings.

In addition, one very recent study focused exclusively on the emissions implications from the introduction of PHEV technology was conducted jointly by the Natural Resources Defense Council (NRDC) and EPRI. Two reports were produced and recently published from this joint study, which claim to be the most comprehensive environmental assessment of electric transportation to date. Volume 1 of NRDC and EPRI study estimated the net greenhouse gas emissions and Volume 2 presents results based on extensive modeling of air quality impacts from the introduction of PHEVs.

The two original EPRI WG studies presented a "well to wheels" emissions analysis of the entire fuel cycle. This includes emissions associated with extraction, processing, and distribution of gasoline and the stack emissions from power plants used to charge PHEVs (these are referred to as upstream emissions or fuel-cycle emissions), in addition to the tailpipe emissions. Sophisticated emissions

models were used to estimate fuel-cycle emissions and the ADVISOR model was used to estimate tailpipe emissions.

The specific pollutants assessed included CO₂ and smog precursors (NO_x and HC). Emissions per mile of travel were calculated for a comparable conventional vehicle, hybrid electric vehicle (HEV), PHEV20, and PHEV60. It was assumed that the conventional vehicle and the HEV meet the Super Ultra Low Emission Vehicle (SULEV) standards and that the plug-ins are charged at night with efficient combined cycle power plants using natural gas as a fuel source. Table 3 presents the results of the EPRI WG (2001) report based on an emissions analysis for a mid-size sedan; the values are reported as the percent reduction as compared to a conventional vehicle. The EPRI WG (2002) study found similar results for compact, mid-size SUV, and full-size SUV vehicle configurations with regards to emissions reduction potential of PHEVs over conventional vehicles.

Table 3
Emissions Reduction Potential for Mid-Size Sedan HEVs and PHEVs:
Percent Below a Conventional Vehicle (SULEV)

	HEV	PHEV20	PHEV60
CO ₂	28%	44%	57%
Smog Precursors	15%	35%	52%

The PHEV grid impact study conducted by researchers at the Pacific Northwest National Laboratory (PNL) included an assessment of net emissions from the large-scale penetration of PHEVs nationwide, also using a well to wheels approach. The PNL study used the Argonne National Laboratory’s Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model to estimate the net emissions impacts associated with the introduction of PHEVs. The emissions analysis was performed for the 12 modified North American Electric Reliability Council’s regions to reflect the varying electric generation mix for charging PHEV batteries. The emissions study was based on the estimated technical potential, whereby 73 percent of energy from the light vehicle fleet would come from electricity. The net emissions findings from this study include the following:

- For the nation as a whole, the total greenhouse gases are expected to be reduced by 27% from the projected penetration of PHEVs.
- Total volatile organic compounds (VOCs) and carbon monoxide (CO) emissions would improve radically by 93% and 98%, respectively, as a result of eliminating the use of the internal combustion engine.
- The total nitrogen oxides (NO_x) emissions are reduced (31%), primarily because of the avoidance of the internal combustion process in the vehicle as well as eliminating the refining process to produce gasoline.
- The total particulate emissions (PM10) are likely to increase nationally by 18%, caused primarily by increased dispatch of coal-fired plants.
- The total SO_x emissions are increased at the national level by about 125%, also caused by coal-fired power plants.

(Kintner-Meyer, Schneider, and Pratt, 2007, p. 12)

The PHEV study of Xcel Colorado’s service territory also included a net emissions assessment for three key pollutants: SO₂, NO_x, and CO₂. This study did not include the entire fuel cycle, which included refinery operations but not the emissions associated with fuel extraction and transport. Given that the production cost model used in the study contains parameters for each power plant in Xcel’s

service territory, the researchers were able to estimate the net emissions impacts for each of the four charging scenarios evaluated.

Under all charging scenarios, PHEVs produced fewer CO₂ emissions than both a conventional internal combustion engine vehicle and a non-plug in HEV. Relative to HEVs, NO_x emissions were similar or slightly less under each charging scenario, but significantly below those produced by a conventional vehicle. While the study did not differentiate between urban and non-urban NO_x emissions, the authors speculate that although minor emissions reductions are achieved, there is a significant shift in the source from tailpipe to stack emissions, which could offer significant smog reduction benefits in the greater Denver metropolitan area. Finally, comparative SO₂ emissions were not consistent over the four different charging regimes modeled. For the daytime and delayed charging scenarios, total PHEV-related SO₂ emissions are expected to be less than those from conventional and hybrid vehicles. In contrast, the off-peak charging case SO₂ emissions are expected to be greater. This result is due to the fact that coal-fired power plants tend to be the marginal units during off-peak hours.

National Renewable Energy Laboratory researchers Peter Lilienthal and Howard Brown (2007) produced estimates of the potential carbon emission reductions from PHEVs by 2030. As mentioned above, this analysis was part of a larger study commissioned by the American Solar Energy Society. The Lilienthal and Brown (2007) analysis did not look at the total carbon emissions reduction potential based on projected PHEV penetration scenarios, but instead estimated the percentage of per mile driven carbon emissions reductions from substituting electricity for gasoline. They found that, on a nationwide average, carbon dioxide emission would be reduced by 42 percent for each mile driven with electricity. The results varied widely across states with some states seeing no potential reductions in carbon from a transition from gasoline to electricity for drive energy such as North Dakota, which relies mostly on low-Btu lignite coal (Lilienthal and Brown, 2007). In some regions, however, the potential reductions were very high, including Vermont with a carbon emission reduction potential of over 80 percent.

Volume 1 of the EPRI/NRDC environmental assessment of PHEVs investigates the nationwide greenhouse gas (GHG) emissions for the 2010 – 2050 timeframe under three different PHEV market penetration scenarios. In the high penetration scenario, PHEVs achieve 80 percent new vehicle market share. In addition, three scenarios for GHG intensities of the power sector were considered. The low carbon intensity scenario has total GHG emissions from the power sector decline by 85 percent between 2010 and 2050. Sophisticated energy sector models of both the electric power and transport sectors were used during the 18-month study to evaluate each combination of these scenarios for a total of nine different possible outcomes, which led to the following conclusions:

- Annual and cumulative GHG emissions are reduced significantly across each of the nine scenario combinations.
 - Annual GHG emissions reductions were significant in every scenario combination of the study, reaching a maximum reduction of 612 million metric tons in 2050 (High PHEV fleet penetration, Low electric sector CO₂ intensity case).
 - Cumulative GHG emissions reductions from 2010 to 2050 can range from 3.4 to 10.3 billion metric tons.
 - Each region of the country will yield reductions in GHG emissions.
- (EPRI and NRDC, 2007: 1, p. 2)

The second volume describes the US air quality analysis that was conducted based on the assumptions contained in the US DOE Energy Information Administration's Annual Energy Outlook 2006 for the year 2030. The study modeled the transportation and electric power sectors in the year 2030 to investigate the impact of PHEVs on criteria emissions and subsequent effects on air quality and deposition. The study was based on PHEVs reaching 50 percent of new car sales and representing 40 percent of the total on-road vehicles in 2030. It is assumed that 20 percent of the total vehicle miles traveled in the US in 2030 use electricity. Again, very sophisticated energy sector modeling was conducted to predict the air quality implications from a shift from gasoline to electricity for transportation. The key findings from the EPRI/NRDC air quality assessment are as follows:

- In most regions of the United States, PHEVs result in small but significant improvements in ambient air quality and reduction in deposition of various pollutants such as acids, nutrients and mercury.
- On a population weighted basis, the improvements in ambient air quality are small but numerically significant for most of the country.
- The emissions of gaseous criteria pollutants (NO_x and SO₂) are constrained nationally by regulatory caps. As a result, changes in total emissions of these pollutants due to PHEVs reflect slight differences in allowance banking during the study's time horizon.
- Considering the electric and transportation sector together, total emissions of VOC, NO_x and SO₂ from the electric sector and transportation sector decrease due to PHEVs. Ozone levels decreased for most regions, but increased in some local areas. When assuming a minimum detection limit of 0.25 parts per billion, modeling estimates that 61% of the population would see decreased ozone levels and 1% of the population would see increased ozone levels.
- Mercury emissions increase by 2.4% with increased generation needs to meet PHEV charging loads. The study assumes that mercury is constrained by a cap-and-trade program, with the option for using banked allowances, proposed by EPA during the execution of the study. The electric sector modeling indicates that utilities take advantage of the banking provision to realize early reductions in mercury that result in greater mercury emissions at the end of the study timeframe (2030).
- Primary emissions of particulate matter (PM) increase by 10% with the use of PHEVs due primarily to the large growth in coal generation assumed in the study.
- In most regions, particulate matter concentrations decrease due to significant reductions in VOC and NO_x emissions from the transportation sector leading to less secondary PM.

(EPRI and NRDC, 2007: 2, p. 4)

To date, the studies of net emissions suggest a clear benefit in terms of reduced CO₂ emission as more and more PHEVs are introduced onto the nation's highways. This result is driven largely by the efficiency improvements along the electricity generation path as compared to the fuel-cycle chain for gasoline, from crude oil extraction, refining, transportation, to ultimate combustion in the vehicle's engine (Kintner-Meyer, Schneider, and Pratt, 2007). In contrast, the net emission impacts from other pollutants are uncertain. Nationwide there seems to be general air quality benefits, however the results can vary significantly across regions as the electric supply mix changes from location to location. Future outcomes are also highly dependent on how the electric power supply mix changes over time. If the electric power supply mix becomes cleaner over time, this would serve to reinforce the air quality benefits of an emerging fleet of PHEVs.

D. PHEV Petroleum Displacement Potential and Equivalent Costs (Electricity vs. Gasoline)

This section of the literature review turns to two additional benefits that PHEVs may offer. In light of rising gasoline prices and the so-called “peak oil” phenomenon, PHEVs are of interest in terms of the potential to displace oil as a fuel for transportation. The ability to substitute a domestic resource for foreign oil is very attractive to policymakers and in some circles is viewed as a critical foreign policy initiative. On the consumer side, PHEVs allow households to substitute a low-cost energy source (electricity) for a higher cost source (gasoline). Here we briefly review what the literature on PHEVs has found on these two fronts.

The EPRI (2001) study estimates that a single mid-sized sedan PHEV20 can save approximately 2,000 gallons of gasoline over its life (100,000 miles) compared to a comparable internal combustion engine vehicle. A simple calculation assuming a price \$2.50 per gallon of gasoline results in total savings of \$5,000. To calculate net savings, the cost of electricity must be subtracted from the avoided fuel expenditures on gasoline. Using the mileage base probability discussed earlier, a PHEV20 could meet, on a statistical basis, an average of 40 percent of total miles traveled. This would translate into 40,000 all-electric miles over the life of the vehicle for a total of 11,460 kWh consumed, assuming an all-electric efficiency of 3.49 miles/kWh. At \$0.10/kWh this would translate into \$1,150 worth of electricity purchased over 100,000 miles of travel. Thus, the net fuel cost savings over the 100,000 miles would be \$3,850. Similarly, the Lemoine, Kammen, and Farrell, (2007) study of California estimated present value fuel savings over 14 years from a PHEV20 over a conventional vehicle to be \$3,726 assuming \$3.00/gallon and \$0.10/kWh. They also find that the fuel savings of a PHEV20 relative to an HEV would be just \$1,000. Thus, they conclude that if consumers have low discount rates over long periods they may find a PHEV economical compared to a conventional vehicle, but not to an HEV.

Kintner-Meyer, Schneider, and Pratt (2007) in their study estimate total potential petroleum displacement from providing 73 percent of the daily energy needs of the light-duty vehicle fleet with electricity through widespread deployment of PHEVs. In this scenario 271 million PHEVs with 33 miles of all-electric ranges would reduce gasoline consumption, by crude oil equivalence, by 6.5 million barrels per day, which is equivalent to 52 percent of current US foreign petroleum imports. Furthermore, Markel et al. (2006) calculate that 1,000,000 PHEVs would save approximately 10 million barrels of oil annually. Certainly, the petroleum displacement potential that PHEVs could achieve is significant, and depends on the number of PHEVs on the nation’s highways and the percentage of miles delivered from electricity, either in all-electric or blended modes.

A popular way to express the economics of PHEVs from a consumer’s perspective is to estimate the cost to purchase an amount of electricity that delivers an equivalent number of drive miles as a gallon of gasoline, the so called cost of “electric fuel”. One dollar or less is often quoted as the cost equivalent of the electrical energy that delivers the same miles of travel as one gallon of gasoline (www.pluginpartners.org). This calculation is quite simple. For example, Denholm and Short (2006) estimate the cost of electricity to drive the equivalent distant as a vehicle getting 30 mpg. Assuming 2.9 miles/kWh for a mid-size sedan, 10 kWh of electricity would be needed. At a cost of \$0.08/kWh results in an electric fuel equivalent cost of \$0.80/gallon gasoline equivalent.

The electric equivalent energy cost as compared to gasoline is sensitive to several key assumptions. The first is the reference vehicle. Given the calculations above, if we use an HEV as the reference

vehicle at 50 mpg, the electric equivalent cost of gasoline would be \$1.38. The second key variable is the efficiency assumption of the PHEV, if we assume a full-size SUV at 2.3 miles/kWh and using an HEV as the reference vehicle brings the electric equivalent cost of gasoline to \$1.74. Finally, the price of electricity is also a key factor in these calculations. In a high-cost electricity region, at \$0.15/kWh, assuming an HEV as the reference vehicle and the electric efficiency of a full-size SUV would result in the electric energy cost of \$3.26 per gallon equivalent. However, given the fact that PHEVs would charge at night, it is reasonable to assume that lower than average rates would apply. Under even conservative assumptions for each of these key variables, electricity is less expensive than gasoline as an energy source for light vehicles at today's fuel prices of approximately \$3.00/gallon.

E. Vehicle to Grid (V2G) Opportunities

Typically, electric utilities view PHEVs and other electric vehicles connecting to the grid as new load. Over the past ten years, however, an emerging literature has developed that expands this view and considers the potential role that grid-connected cars could serve as distributed energy storage devices. A bi-directional charger could allow power to both flow into the battery pack and out of the pack to the electric grid serving any number of grid services (Kempton and Letendre, 1997). Depending on the size of the battery pack and power rating of the plug circuit, a V2G capable vehicle could potentially generate hundreds of dollar, or perhaps thousands of dollars, annually providing ancillary services to the electric utility sector (Letendre, Denholm, and Lilienthal, 2006). Interest in V2G technology has increased significantly in recent years. A Google web search using the term “vehicle to grid” yields 35,000 hits. A number of technology and commercial development efforts are currently underway to facilitate grid-interactive vehicles based on the V2G concept. Among other projects, the California utility Pacific Gas & Electric recently demonstrated a V2G capable PHEV and is working with the philanthropic organization Google.org to advance this concept.

This phase of the PHEV Vermont study does not address V2G. In future phases, however, the University of Vermont's Transportation Center and Green Mountain College plan to develop projects that explore V2G opportunities in Vermont.

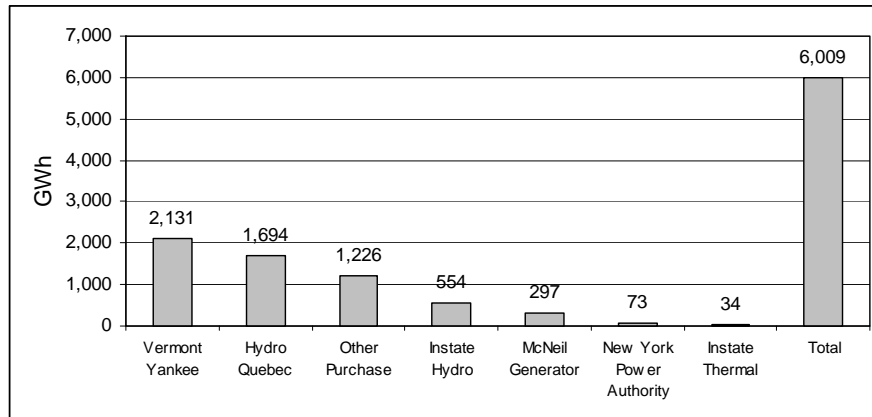
III. Proposed Methodology for Vermont PHEV Study

Vermont is a small state with strong environmental values. In Vermont there are approximately 615,000 vehicles—state vehicles, municipal vehicles, trucks, and autos—registered for a population of around 620,000 (Glitman and Wang, 2007). Similarly, the electric power sector that serves the state's approximately 340,000 electric customers is small compared to the nation and the region delivering just over 6 GWh of energy each year.

The electric power sector in the state is fragmented with 4 investor-owned utilities, 15 municipal electric departments, and 2 member-owned rural electric cooperatives. The four largest utilities—Central Vermont Public Service (IOU), Green Mountain Power (IOU), Vermont Electric Coop, and the Burlington Electric Department (municipal)—serve 87 percent of the state's electricity customers. Vermont's power supply comes primarily from Vermont Yankee, a nuclear power facility located in

Vernon, VT and a purchase power contract with Hydro Quebec. The contracts for both of these power sources are set to expire within a decade, thus much uncertainty exists about Vermont’s future power supply. Figure 3 presents the total GWh consumed in 2003 from each of the various sources meeting the state’s electricity requirements.

Figure 3
Vermont’s 2003 Energy Supply Mix (GWh)



Source: Vermont Department of Public Service

The Vermont bulk transmission system is operated by VELCO, which is a regulated utility owned and controlled in various percentages by 14 of the state’s electric utilities. Central Vermont Public Service and Green Mountain Power own 86 percent of VELCO. VELCO was originally formed in 1956 to develop an integrated transmission system in the state, and today conducts a variety of planning and reliability functions, and serves as the representative of the state’s electric utilities to the Independent System Operator (ISO) of New England, the organization that controls the New England grid to assure reliable and efficient operation of the regional power system. ISO New England also manages the region’s wholesale power markets. Vermont is considered one of eight zones that comprise the New England grid.

Vermont was the first state to organize an efficiency utility, charged with the sole purpose of assisting Vermont energy consumers to manage and reduce their electricity consumption. Efficiency Vermont (EVT), operated by the non-profit Vermont Energy Investment Corporation, has gained national recognition for its programs and has served as a model for other states across the country. A small per kWh charge is added onto electric rates to provide a pool of funds for EVT to pursue numerous efficiency programs to help Vermont households and businesses become more efficient in their use of electricity.

A. Assessing PHEV Load Impacts in Vermont

This study will adopt a bottom-up approach to assessing the load impacts from an emerging fleet of PHEVs, similar to three of the grid impact studies reviewed earlier. A composite plug-in hybrid vehicle profile will be developed based on the types of new vehicles purchase in Vermont that has an all-electric range of 20 miles—a so-called PHEV20. According to a report by RL Polk, commissioned by the University of Vermont Transportation Center, over 25 percent of new cars purchased in 2006

were smaller vehicles, over 40 percent were medium-sized, and over 30 percent were larger vehicles (Watts, Glitman and Wang, 2007). Based on a review of the literature, a PHEV20 was assumed in most studies and represents a likely architecture of first-generation PHEVs as it is expected that battery storage costs will be a key factor in designing an affordable PHEV.

Three different PHEV penetration scenarios will be assessed. The low penetration scenario will evaluate the grid impacts of a fleet of 100,000 PHEVs, or approximately 16 percent of total vehicles currently registered in Vermont. The second scenario will assume a fleet of 300,000 PHEVs or approximately one half of the light vehicle fleet in the state. The high penetration scenario at 500,000 vehicles, while not likely within a reasonable planning timeframe, will serve to establish an upper bound impact on the Vermont grid from an emerging fleet of PHEVs. Furthermore, the high penetration scenario serves to highlight possible impacts from a smaller number of all electric vehicles or PHEVs with higher all-electric ranges than a PHEV20, both of which would create higher per vehicle consumption of electricity.

Hourly load data for the entire state of Vermont will be acquired. The peak day in each of the four seasons will be identified and used as the basis to calculate the seasonal load impacts from the three different PHEV penetration scenarios described above. The seasons are defined as follows:

- Winter—December, January, and February.
- Spring—March, April, and May
- Summer—June, July, and August
- Fall—September, October, and November

This study will adopt the three charging scenarios used by Lemoine, Kammen, and Farrell (2007) in their study of the impacts of PHEVs in California's energy market. These three scenarios, listed again below, represent three possible scenarios in terms of consumer charging preferences. It is informative to understand the system-wide load impacts from these three different charging scenarios. In doing so, it may serve to assess how critical incentives or direct utility control may promote charging that does not add to system peak demands.

1) Optimal Charging. This corresponds to the best case assumptions used in prior analyses. It is optimal from the grid operator's perspective. The vehicles are charged in a pattern that smoothes demand as much as possible by charging during periods of lowest demand, and vehicles need not charge for 5 continuous hours. This scenario bounds the possible beneficial load-leveling effects of PHEVs.

2) Evening Charging. The times at which the PHEVs begin charging are evenly distributed between 6, 7, and 8 PM. Each PHEV charges for 5 continuous hours. This represents drivers returning home from work and plugging in their vehicles. This and the next scenario are meant to provide worst-case baselines for possible behavior in the absence of price incentives or technical means of shaping charging patterns.

3) Twice Per Day Charging. This is a high demand scenario: each PHEV is assumed to be plugged in to charge fully at the end of each commute leg. Thus, each vehicle fully charges twice each day, once upon arriving at work in the morning and once upon arriving home in the evening. Charging start times are evenly distributed between 8 and 9 AM and again between 6, 7, and 8 PM. Each PHEV charges for 5 continuous hours in the morning and again in the evening. (Lemoine, Kammen, and Farrell, 2007, p. 4)

The final output from this analysis will be 12 different line charts produced using MS Excel. The line charts will depict 24-hour load curves. Three charts will be produced for each season, each one depicting a different PHEV penetration scenario. Each individual chart will depict the load impacts from the three different charging scenarios. Analysis and discussion of the results will be performed as well. Table 4 presents a summary of the proposed scenarios to assess the grid impacts of an emerging fleet of PHEVs in Vermont.

Table 4
Proposed Scenarios for PHEV Grid Impact study

Chart #1	100,000 PHEVs, Winter Load Profile, 3 charging scenarios
Chart #2	300,000 PHEVs, Winter Load Profile, 3 charging scenarios
Chart #3	500,000 PHEVs, Winter Load Profile, 3 charging scenarios
Chart #4	100,000 PHEVs, Spring Load Profile, 3 charging scenarios
Chart #5	300,000 PHEVs, Spring Load Profile, 3 charging scenarios
Chart #6	500,000 PHEVs, Spring Load Profile, 3 charging scenarios
Chart #7	100,000 PHEVs, Summer Load Profile, 3 charging scenarios
Chart #8	300,000 PHEVs, Summer Load Profile, 3 charging scenarios
Chart #9	500,000 PHEVs, Summer Load Profile, 3 charging scenarios
Chart #10	100,000 PHEVs, Fall Load Profile, 3 charging scenarios
Chart #11	300,000 PHEVs, Fall Load Profile, 3 charging scenarios
Chart #12	500,000 PHEVs, Fall Load Profile, 3 charging scenarios

B. Assessing PHEV Net Emissions Impacts in Vermont

The emissions analysis will focus on six specific pollutants, generally linked to Vermont’s transportation and electric power sectors. These pollutants include: carbon dioxide (CO₂); carbon monoxide (CO); volatile organic compounds (VOC); particulate matter (PM); nitrogen oxide (NO_x); and sulfur dioxide (SO₂). A base case emissions profile will be produced using secondary sources of data on emissions in Vermont for both the light vehicle fleet and the electric power sector. This base case emissions profile will be compared to emissions profiles for the different scenarios evaluated under the system load impact assessment described above (see Table 4 above).

Two different vehicle emissions profiles will be developed based on the three different charging scenarios for each of the three PHEV penetration scenarios. The evening charging and optimal charging scenarios will result in the same amount of annual gasoline reductions, while the twice per day charging scenario results in greater use of electricity and less use of gasoline than the two other charging scenarios. As a result six

different light vehicle fleet emissions profiles will be produced, two for each of the three PHEV penetration scenarios as follows:

1. PHEV penetration 100,000 (optimal and evening charging);
2. PHEV penetration 100,000 (twice per day charging);
3. PHEV penetration 300,000 (optimal and evening charging);
4. PHEV penetration 300,000 (twice per day charging);
5. PHEV penetration 500,000 (optimal and evening charging); and
6. PHEV penetration 500,000 (twice per day charging).

Total emissions using current electricity consumption given the Vermont supply mix will serve as the base case emissions for the power sector. Stack emissions associated with power production can vary by time of day and season of year. For this study the increased stack emissions associated with PHEV charging will depend on the specific power resources used to charge the batteries over a given annual cycle. Given that Vermont is linked to the New England grid, the methodology adopted here calls for the use of marginal emission rates as calculated by the Independent System Operator of New England (ISO-NE). ISO-NE produces marginal emissions rates for each hour of the operating year, which will be used to calculate the net change in power sector emissions in Vermont from an emerging fleet of PHEVs.

Again, the increased stack emissions from charging PHEVs will depend on the charging scenario considered. The evening and optimal charging scenarios will increase electricity consumption by the same amount, but the charging will occur at slightly different times. As indicated in the study of Xcel Energy's Colorado service territory by Parks, Denholm, and Markel (2007) charging at different times of the day results in dissimilar emissions impacts due to the fact that a different set of resources can be on the margin during each operating hour. The twice per day charging scenario will result in greater electricity consumption as compared to the evening and optimal charging scenarios. The marginal emissions for nine different scenarios—three different PHEV charging scenarios and the three PHEV penetration scenarios—will be added to the base case to calculate total emissions from the electric power sector. Thus, ten different emissions profiles associated with power plant stack emissions will be produced as follows:

1. Base case electric power sector emissions given 2006 energy consumption
2. Base case plus marginal emissions from 100,000 PHEV, optimal charging
3. Base case plus marginal emissions from 100,000 PHEV, evening charging
4. Base case plus marginal emissions from 100,000 PHEV, twice per day charging
5. Base case plus marginal emissions from 300,000 PHEV, optimal charging
6. Base case plus marginal emissions from 300,000 PHEV, evening charging
7. Base case plus marginal emissions from 300,000 PHEV, twice per day charging
8. Base case plus marginal emissions from 500,000 PHEV, optimal charging
9. Base case plus marginal emissions from 500,000 PHEV, evening charging
10. Base case plus marginal emissions from 500,000 PHEV, twice per day charging

The baseline transportation sector and power sector emissions will be combined and compared against the combined emissions profiles for each of the nine different scenarios being studied: three different PHEV penetration scenarios and three different charging patterns. This comparison will serve to assess the net emissions impacts from an emerging fleet of PHEVs in Vermont.

C. Petroleum Displacement Potential and End-User PHEV Economics

Estimates of annual reductions in gasoline consumption will be produced for each of the scenarios described in section A above, *Assessing PHEV Load Impacts in Vermont*. Gasoline displacement is a function of the number of PHEVs operating in Vermont and the percentage of total drive miles from electricity. In addition, the reference vehicle for comparison purposes is also important to estimate future petroleum displacement opportunities. For this study, we will assume two different reference vehicles. First, we will assume that the PHEVs that enter the market are replacing conventional internal combustion engines. This will provide an upper bound estimate of the petroleum displacement potential of PHEVs here in Vermont. Next, the study will consider the petroleum displacement potential assuming that PHEVs displace comparable standard hybrid electric vehicles, without the ability to charge from the electric grid.

Ultimately, the economics from an end-user perspective will drive the market for PHEVs in Vermont. This study will provide a model to evaluate the lifecycle costs of owning and operating a PHEV relative to a conventional vehicle. For simplicity, maintenance costs will be assumed to be equivalent between the comparison vehicles. Thus, the analysis will focus on the fuel costs to operate a PHEV over its life, which will be compared to both a conventional and standard non-plug in hybrid electric vehicle. These calculations will be performed for a mid-sided sedan PHEV20. In addition, electric rates for each of Vermont's major utilities will be used to calculate and electricity equivalent cost of a gallon of gasoline. The equations presented in the literature review section above will be adapted for this purpose. Again, these calculations will be performed for a mid-sized sedan PHEV20 using two different reference vehicles, a conventional internal combustion vehicle and a conventional hybrid electric vehicle.

IV. Results

Draft results to be completed by mid-November, 2007.

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